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# Unresolved Puzzles in the X-ray Emission Produced by Charge Exchange Measured on Electron Beam Ion Traps

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**Abstract.** Charge exchange recombination, the transfer of one or more electrons from an atomic or molecular system to a positive ion, is a common phenomenon affecting laboratory and astrophysical plasmas. Controlled studies of this process in electron beam ion traps during the past one and a half decades have produced multiple observations that are difficult to explain with available spectral models. Some of the most recent observations are so puzzling that they bring in doubt the existence of a coherent predictive capability for line formation by charge exchange, making investigations of charge exchange a fertile ground for continued measurements and theoretical development.

**Keywords:** Charge exchange, x-ray spectra

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## INTRODUCTION

Charge exchange between ions and neutral atoms or molecules is an important process in many laboratory and astrophysical plasmas, where it can strongly affect the ionization balance and produce spectral lines that are strongly enhanced or otherwise not excited at all. X-ray emission following charge exchange has become of great interest upon the discovery that comets and planetary atmospheres in the solar system are bright x-ray sources because of

their interaction with highly charged, heavy ions in the solar wind [1-3]. Furthermore, it is now believed that most of the soft x-ray background is due to charge exchange in the geocorona and especially in the heliosphere [4,5].

The contributions of line formation by charge exchange to x-ray spectra have been observed on tokamaks [6-8]. In tokamak plasmas, line formation due to charge exchange competes with line formation via electron-impact collisions. An exception was the measurement of the K-shell x-ray spectrum of heliumlike argon, which was produced by plasma ions interacting with a high-energy (40 keV/amu) neutral deuterium beam in the near absence of electron-impact excitation [9].

X-ray spectra produced solely by low-energy (< 50 eV/amu) charge exchange collisions were first produced on electron beam ion traps [10,11], where charge exchange collisions took place *in situ*, i.e. within the trap. A review of such measurements was given by Wargelin, Beiersdorfer, and Brown [12], and many puzzling discrepancies between measurement and theory were noted. In the following, we discuss x-ray measurements conducted since this review. These measurements, some of which have achieved high spectral resolution, have been reaffirmed many of the unresolved discrepancies between experiment and theory found earlier. Even more puzzling is a recent experiment in which two, co-mixed bare ion species of similar atomic number produce very different Lyman series emission upon charge exchange [13], defying both theoretical predictions and empirical scaling.

## EXPERIMENT

Charge exchange measurements on electron beam ion traps are enabled by the so-called magnetic trapping mode [14-16], in which the electron beam is turned off and the ions are confined solely by the magnetic field and the electrostatic potential on the trap electrodes. Early on, x-ray emission was studied using high-purity germanium detectors [16]. These instruments have a resolution of a few hundred eV depending on the energy of the recorded x ray, and they provided spectra of the K-shell x-ray emission produced by charge exchange for ions as high as $Au^{77+}$ and $U^{90+}$ [11,16-18]. For example, a spectrum of $U^{90+}$ produced by charge exchange is shown in Fig. 1.

The advent of x-ray microcalorimeters [19-21] allowed x-ray measurements with much higher resolution than otherwise possible, and K-shell x-ray lines could be (fully) resolved. In fact, the early implementation of the x-ray microcalorimeter on the EBIT-II electron beam ion trap at Livermore already provided a resolution of about 9 eV [19]. More recently, a resolution of 4.5 eV has been achieved [22,23]. The tremendous progress afforded by the

higher resolution instruments is illustrated for the case of argon in Fig. 2. We note that although crystal spectrometers may achieve an even higher resolving power than x-ray microcalorimeters they have not be used to measure the x-ray lines produced by charge exchange. The reason is their comparatively low quantum efficiency.

## UNRESOLVED ISSUES

Because typical solid-state-type x-ray detectors used so far in astrophysical observations have ≥ 100 eV spectral resolution and do not resolve the K-shell emission from upper levels with a high n principal quantum number (cf. Fig. 2(a)), Beiersdorfer et al. [11] defined the hardness ratio $H = F_{3+}/F_2$ in order to extract a measurable and diagnostically meaningful quantity. Here, $F_2$ is the observed flux of transitions from principal quantum number n = 2 to the ground level, and $F_{3+}$ is the sum of flux in transitions from n ≥ 3 to ground. The hardness ratio depends on the collision energy between the ions and the neutral gas [24], and it also depends on the properties of the neutral gas [25,26].

The hardness ratio was measured for numerous K-shell ions at Livermore [11]. As shown in Fig. 3, the measured ratio from hydrogenic ions was determined to be nearly independent of Z and close to unity. In all cases, the measured H was significantly higher than the predictions based on the classical trajectory Monte-Carlo (CTMC) method [11]. This discrepancy, which increases for higher atomic number, has not yet been resolved.

Interestingly, when studying the x-ray emission using argon ions extracted from the Berlin EBIT, a hardness ratio was found that agreed with CTMC predictions much better than the *in situ* ratio [27]. The two ratios obtained by the Berlin group are shown in Fig. 3. The two measurements were expected, of course, to give the same result; the fact that they did not has not yet been explained. In other words, there is no known mechanism of sufficient strength that would change the charge exchange process depending on whether it involves trapped ions or free-streaming, extracted ions.

Even more puzzling is the result obtained by co-mixing bare phosphor and bare argon ions within the Livermore electron beam ion trap [13]. The co-mixed ions are presumed to have the same temperature and to interact with the same neutral gases; this precludes potential differences in the x-ray emission caused by the

collision energy between the ions and the neutral gas or by the properties of the neutral gas. While the measured H for argon falls in line with all previous values measured *in situ*, the measured H for phosphor does not. In fact, the value for phosphor is two times larger than that for argon and than that for all other elements measured within electron beam ion traps [11,13,27]. The CTMC method includes no physical mechanism that would account for such a peculiar ratio pertaining to only phosphor but not to any of the other elements, and this observation remains totally unexplained. Unfortunately, there is no way to predict whether the hardness ratio for a given ion not yet studied follows the pattern set by argon or the pattern set by phosphor, or whether there are yet new patterns to be discovered. In essence, this – and all other unexplained observations already mentioned – means that there is no coherent predictive capability for line formation by charge exchange.

## CONCLUSION

From our brief discussion, we can conclude that x-ray production by charge exchange is still very poorly understood. While spectra can be modeled in an approximate fashion, theory is very far from predicting spectra the way atomic physics can predict x-ray spectra produced by electron-impact excitation. This means that charge exchange is a fertile area of investigation, and such investigations must be pursued, if spectra from laboratory and astrophysical plasma are to be understood and used to extract diagnostically relevant information.

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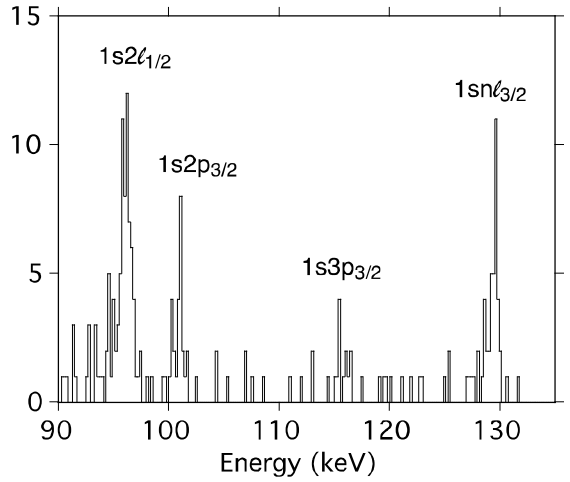


**FIGURE 1.** K-shell x-ray emission from heliumlike $U^{90+}$ produced by charge exchange of neutral gas with $U^{91+}$ ions in the SuperEBIT electron beam ion trap at Livermore. Peaks are labeled with the upper configuration that decays to the $1s^2$ heliumlike ground level.

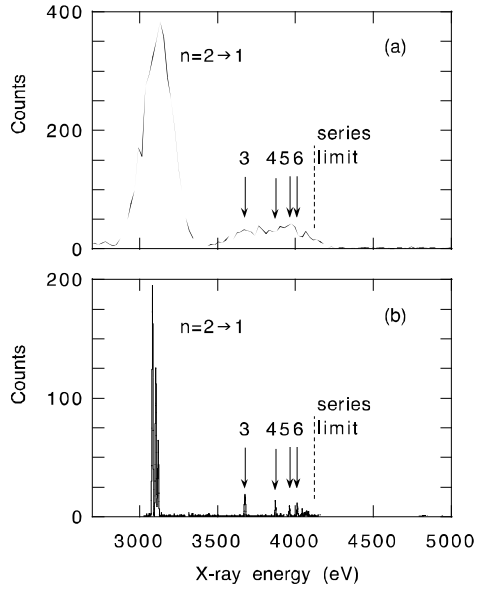


**FIGURE 2.** K-shell x-ray emission from heliumlike $Ar^{16+}$ produced by charge exchange of neutral gas with $Ar^{17+}$ ions: (a) observation with a high-purity Ge detector (cf. measurements in [11); (b) observation with the EBIT Calorimeter Spectrometer (cf. measurements in [13]).

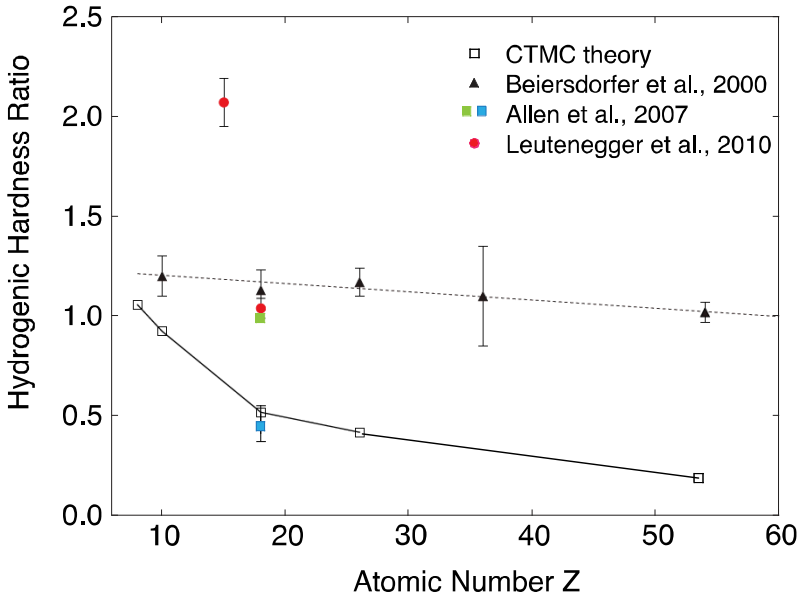


**FIGURE 3.** (Color online) Measured and calculated values of the hardness ratio H of the emission from hydrogenlike ions as a function of atomic number Z. The dashed line is a linear fit to the hardness ratios (solid triangles) measured *in situ* in the Livermore electron beam ion trap and reported in [11]; the solid line connects values predicted by the CTMC theory [11]. A measurement of H for $Ar^{17+}$ obtained *in situ* from the Berlin EBIT is shown as a green square [27]; a measurement of H for $Ar^{17+}$ obtained using extracted ions is shown as a blue square [27]. The measurements of H for $P^{14+}$ and $Ar^{17+}$ obtained concurrently (as a co-mix in the trap) at Livermore are shown as solid red circles [13].